Best Practices in Dam and Levee Safety Risk Analysis

VII-4. Mechanical and Electrical Systems

26 February 2015
1. General Background Information on Dams Throughout the U.S.

2. What Risks are Involved with Operating Gated Structures?


4. Quick Background on Statistical Weibull Distribution Formulas.

5. The Dormant – Weibull Formula

6. Key Elements of the Formula

7. Fault Tree Software

8. Demonstration of Software
The US Army Corps Of Engineers Inventory of Dams (610 Dams)

- Red - High Hazard Potential
- Yellow - Significant Hazard Potential
- Black - Low Hazard Potential

* From the NID
Federal Agencies Provided Information on 5,104 Dams

- Forest Service, NRCS, Air Force, Dept of Energy, USGS did not provide updated NID information
State Participation in Providing Updated Inventory Data to the NID

- 81,372 dams were submitted by the State Dam Safety Offices

- Red - High Hazard Potential
- Yellow – Significant Hazard Potential
- Black – Low Hazard Potential
Problem
Aging Mechanical & Electrical Systems

What risks are involved with operating gates at a our structure?

Issue 1. Will the gates open or close when needed?
Issue 2. Is there a way to predict if the gates will operate when needed?
Issue 3. What are the consequence if the gates don’t operate?

\[
\text{Risk} = \text{Probability of Component Failure} \times \text{Consequence of Component Failure.}
\]
“We also Want to Know”

How Does failure of Mechanical or Electrical Components Affect the Overall Projects Risk Assessment?
How Mech or Elect failures affect Risk “Simple Examples”

• If a spillway gate does not operate during a flood event it can cause overtopping of the structure leading to failure.

• If power fails at a project all operation of gates fail thus increasing the risk of loading on the dam or even overtopping.

• If service gates cannot raise, winter draw down cannot occur thus increasing risk of flooding do to spring rains.
Where does Mechanical or Electrical failure fit into the event tree of a project to predict Overall Risk?
Simple Event Tree

Electrical Power Fails

- High Water or Flood Event
  - Electrical Power Fails
    - All Gates Fail to Operate
      - Yes
        - Electrically will Emergency Spillway take Flow Capacity
          - Yes
            - Electrical affects risk
          - No
            - Will Dam Overtop
              - No
                - Electrical does not affect risk
Simple Event Tree

Mechanical Drive Fails to Open Gate

High Water or Flood Event

- Electrical Power Fails
- Mechanical Drive Fails
- Controls Fail

One Gate Fails to Operate

- Yes
  - Hydraulically Flow Capacity Suffers
  - Mechanical One Gate not Working, Possess Risk
- No
  - Mechanical One Gate not Working, Possess Little Risk
Simple Event Tree

Controls Fail to Open Gate

- High Water or Flood Event
  - Electrical Power Fails
  - Mechanical Drive Fails
  - Controls Fail
    - One Gate Fails to Operate
      - Yes: Controls Cause One Gate not Working Possess Risk
      - No: Hydraulically Flow Capacity Suffers
        - Yes: Controls Cause One Gate not Working Possess Little Risk
        - No:
Predicting/Calculating the Probability of Failure of Dam components

There are two ways of predicting Probability of Failure
* Expert Elicitation
* Statistical Formulas

The Corps researched many statistical formulas for its use in determining the best formula to predict probability of failure of its components and systems.

The Weibull Distribution Formula was selected.
Weibull Distribution Formula

\[ R(T) = \text{Reliability} \]
\[ T = \text{Time} \]
\[ \gamma = \text{Location Parameter} \]
\[ \beta = \text{Shape Parameter} \]
\[ \eta = \text{Characteristic Life} \]
\[ e = 2.718 \]

The Weibull distribution is one of the most widely used lifetime distributions in reliability engineering.

Weibull Distribution was invented in 1937 by Swedish born, Waloddi Weibull. Its used by majority of industrial manufacturing industries throughout the world.
Problem with the traditional Weibull Formula

It doesn’t take into account durations of time when a product is not in use.

Example: Dam gates that are operated only once a month.

Solution: The Dormant - Weibull Formula

\[ Q_n = 1 - \exp \left( \frac{(n-1)\tau - \gamma}{\eta} \right)^\beta \cdot \exp \left[ -\frac{(n\tau - \gamma)^\beta}{\eta} \right] \]

\( Q_n \) = Probability of Failure over the entire interval \( n \)
\( \eta \) = Characteristic Life Parameter
\( \beta \) = Shape Parameter
\( \gamma \) = Location Parameter
\( \tau \) = Inspection Interval or time since last operated
\( n \) = Number of times the component operated in its life.
1st Key Element in the Formula

\[ \eta = \text{Characteristic life} \]

Definition: The characteristic life is the point in time when we could expect 63.2% of the components under study to have failed.

Example: It's determined that the characteristic life of a component is 25 years, then you would expect to have 63 of 100 components fail by that time in history.

Characteristic life is traditionally gathered through testing of thousands of samples.

The Corps has gone through a rigorous data search of its inventory of dams and compiled a list of how many and how long its mechanical and electrical component have lasted in real world applications. This data has been placed on a Weibull curve to determine the characteristic life of its components.
Adjustments to Characteristic life

When the Corps performed its data search to determine the characteristic life, it considered the components life over the entire range of projects throughout the U.S. with average maintenance.

In reality components have a varying characteristic lives depending on environments and conditions there operated in.

To adjust for environment, stress and temperature factors the characteristic life is adjusted by a predetermined factor.

Existing condition of the components are taken into account by inspections. A (A-F) scale is used to rate the condition of the component for corrosion, wear, etc. Condition is also used to adjust the characteristic life of a component.

Example: If a component is showing extreme wear at a early stage of its life then the characteristic life of the component is adjusted down by a predetermined factor. Or if it is exposed to a harsh salt water environment or heavy silt build up.
2nd Key Element in the Formula

\[ \beta = \text{Beta Shape Parameter} \]

\[ \beta < 1 \quad \text{Implies quality problems or insufficient “Burn In”. Usually associated with beginning of a components life.} \]

\[ \beta = 1 \quad \text{Random failures or failures independent of time in service.} \]

\[ \beta > 1 \quad \text{Wear out failures at a definite or predictable end of life. Typically age related due to service conditions such as corrosion, wear, or fatigue cracking.} \]

The Corps uses a combination of Beta Shape Parameter factors from ETL 1110-2-560, dated 30 June 2001, and the statistical data it has collected on components.
3rd Key Element in the Formula

\( \gamma = \text{Location Parameter} \)

\( \gamma = \text{Location Parameter} \) is the difference in years between when the component was originally installed and when it was replaced.

Example: If a component was originally installed in 1965 and was replaced in 1995 the location parameter would be.

1995 – 1965 = 30 years

If the component is original then the location parameter = 0.
4th Key Element in the Formula

\[ t = \text{Inspection Interval} \]

\( \tau = \text{Inspection Interval. Time in (years) between when the component was last inspected or operated properly to present.} \)

Example: A component was last operated 1 month ago.

\( \tau = 1 \text{ month/12 months per year} = 0.0833 \)
Final Results

A formula which predicts a component's probability of failure as of this year.

Example: An 25 year electric motor with a characteristic life of 80 years which was last operated 1 month ago in a normal environment would have a probability of failure of .001 this year.

\[ Q_n = 1 - \exp\left[\left((300-1)\cdot0.0833-0)/80\right)^1\right] \exp\left[-\left((300\cdot0.0833-0)/80\right)^1\right] = .001 \]
We want More

Knowing the probability failure of a individual components is good but we want to know what the systems probability of failure is.

To find the solution the Corps relies on a fault tree program.

The Corps reviewed up to a halve dozen types of software packages which performed fault tree analysis.

Isographs, Fault Tree software was establishes as the superior program for ease of operation and usefulness to the Corps.
Fault Tree Software

Probability of Failure to Operate Gates

Gate Fails to Operate

OR GATE
Q = 0.02783

Or Gate

Gate Operation Controls Fail
Q = 0.007

Gates Mechanical Drive Fails
Q = 0.02

Electrical Power Source Fails
Q = 0.001
Fault Tree Software

Probability of Hydraulic Power Failure

- Both Pumps Fail to Operate
  - AND GATE
    - Q=0.0002
  - Pump #1 Fails
    - MECHANICAL
      - Q=0.02
  - Pump #2 Fails
    - ELECTRICAL
      - Q=0.01
Fault Tree Software

Wire Rope Drive System

25 Year old components
Operated 1/month

1A
Q=1.101e-2

Brake Electrical Elements
1A1
eta=30 tau=0.083
Q=2.875e-3

Brake Mech Pads & Springs
1A2
eta=60 tau=0.083
Q=7.216e-4

Coupling Flexible
1A3
eta=40 tau=0.083
Q=2.126e-3

Coupling Rigid
1A4
eta=60 tau=0.083
Q=1.389e-3

Motor to Gear box Connecting Rotating Shaft
1A5
eta=100 tau=0.083
Q=7.946e-4

Gear Reducer
1A6
eta=60 tau=0.083
Q=7.216e-4

Right Angle Gear
1A7
eta=40 tau=0.083
Q=2.433e-3
Example of a Simple Fault Tree for a Flood Control Gate
Demonstration Time

The excel spreadsheet for calculating characteristic life and probability of failure of components.

The Isograph Reliability Workbench software demonstrating a typical probability of failure of a dam gate.

Note: There are other vendors of fault tree software. Isograph, Reliability Workbench, is just one such software package.